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Nordic Hydrology, 33 (1), 2002, 15-26
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Inter-Comparison of two Snow Models with Different Complexity using Data from an Alpine Site

Selected paper from EGS General Assembly, Nice,
April-2000 (Symposium OA36)

U. Strasser
Inst.Hydromech. & Water Res. Mgm., ETH, Zürich, Switzerland
P. Etchevers and Y. Lejeune
CEN/CNRM, METEO France, Saint Martin d'Hères

This contribution describes the modelization of the snow cover evolution with the two physically based snow models CROCUS and ESCIMO at the Col de Porte station (1,325 m a.s.l., French Alps) for the three subsequent seasons 1994/95–1996/97. CROCUS is a detailed, multi-layer snow model developed for the operational avalanche forecasting system of METEO France, whereas ESCIMO is a one-layer energy and mass balance snow model for hydrological applications. The snow albedo function parameters for ESCIMO are calibrated in 1994/95. In the first verification season (1995/96), the results of the two models show a good correspondence, whereas in the second (1996/97) they differ significantly. For this season a considerable gain in performance of ESCIMO is achieved by recalibration of the snow albedo function parameters.

Introduction

An important component of the water cycle in mountainous areas is the water equivalent of the seasonal snow cover (SWE). The knowledge of its temporal storage can be valuable for the prediction of seasonal discharge, short-term flood forecasts caused by spring snow melt, the assessment of water quality aspects and even tourist needs. Usually direct measurements of the SWE are not part of standard meteorological observation programs; therefore, snow models utilizing meteorological measurements are used to simulate its seasonal evolution. If the goal of the investigation is to forecast the timing and rate of snowmelt from limited input data, then simple

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degree-day index models proved to be valuable tools. In contrast, physically-based models, which indeed require input data with comparably high temporal resolution, are utilized for the examination of individual physical processes and for the analysis of the discharge sensitivity of the environmental conditions such as land use or climate change scenarios.

In recent times several physically-based, sophisticated multi-layer snow models have been developed to describe in detail the seasonal evolution of each single layer of the snow pack (*e.g.* Lehning *et al.* 1998; Brun *et al.* 1992; Blöschl *et al.* 1991; Jordan 1991). These models are mainly used as part of operational meteorological forecasting systems for the prediction of avalanche risk. However, for distributed applications on larger scales the needs of the required input can often not be met in terms of their accuracy and temporal resolution. Furthermore, for hydrological investigations the duration of the snow cover and accurately simulated melt rates are rather a matter of particular interest than the description of the state of its internal layers. Simple bulk snow models have proved to be efficient tools for such purposes: In many case studies they are coupled with SVAT-models for long-term water cycle modelizations using a continuous time series of meteorological input data (Braden 1995; Habets *et al.* 1999; Strasser 1998) or applied in conjunction with runoff models for the simulation of glacier discharge in mountainous catchments (*e.g.* Escher-Vetter 2000; Arnold *et al.* 1996; Braithwaite and Olesen 1990; Baker *et al.* 1982).

In this study two physically based representatives of the both groups of snow models are compared for the point scale using the same set of hourly meteorological observations: CROCUS is a detailed, multi-layer snow model developed for the operational avalanche forecasting system of METEO France, whereas ESCIMO is a one-layer energy and mass balance snow model for hydrological applications. Its fundamental principles are presented in this paper.

Meteorological Data

The meteorological observations used in the model comparison were captured at the Col de Porte station which is located in the Massif de la Chartreuse in the northern French Alps at 1,325 m a.s.l. (45°N, 6°E) (David and Martin 1997). There the typical climatic conditions are characterized by sequences of daily to weekly cold and warm periods. The mean annual precipitation amount is ~2,000 mm with a continuous snow cover usually existing from late November to the beginning of May. The deep snow layers are wet most of the time, whereas the upper snow layers are submitted to strongly varying conditions depending on the meteorological conditions: they include heavy, dry snow falls, long dry periods, rain on snow, complete refreezing, late spring snow falls and high temperature gradients. The following parameters necessary as input data for the intended simulations are measured every hour: air

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temperature, humidity, liquid and solid precipitation, wind speed and visible as well as infrared radiation. For validation issues the snow height (daily) as well as the snow water equivalent SWE (weekly) are measured. Due to its variable climatic conditions the chosen location is well suited to testing how the two models CROCUS and ESCIMO are able to simulate the response of the snow pack to the main meteorological phenomena affecting it.

The CROCUS Snow Model

CROCUS is a physically based, one-dimensional snow model calculating the energy and mass evolution of the snow cover as a function of the meteorological conditions (Brun *et al.* 1989, 1992). It was developed for the prevision of avalanche risk and is now part of the operational forecasting system of METEO France. CROCUS simulates the evolution of temperature, density and liquid water content for up to 50 layers of the snow pack parallel to the slope with their thickness being a variable of depth and time. The physical processes simulated by CROCUS are the energy exchanges inside the snow pack and at the snow-soil and snow-atmosphere interfaces, the absorption of solar radiation with depth, the phase changes between solid and liquid water, the water transmission through the snow pack, the mass exchanges due to precipitation and melt water runoff, the settlement and the metamorphism of snow. The latter is controlled by the grain type which is defined by its dendricity, sphericity and size. The snow albedo and extinction coefficient depend on the wavelength of the incoming radiation and the type, size and age of the surface snow layer.

The ESCIMO Snow Model

ESCIMO is a physically based energy and mass balance snow model for a single snow layer designed for hydrologic purposes. At each hourly time step ESCIMO calculates the energy balance, the water equivalent and the melt of a snow cover. For the simulation of the energy balance the short- and longwave radiation, the sensible and latent heat fluxes, the energy conducted by solid or liquid precipitation and a constant soil heat flux are taken into account. The snow albedo is modelled using a function considering the age and the surface temperature of the snow pack. For each time step the following scheme, based on the one adopted in SHE (Abbott *et al.* 1986), is followed: calculation of the energy balance, decision whether the precipitation is solid or liquid (if not measured), estimation of the water mass and energy budget based on the hypothesis of no snowmelt at the current time step, comparison of the total available energy with that sustained as snow by the total available mass at 273.16 K, modelization of the snowmelt produced by the excess energy and up-

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date of the mass and energy budget. Several snow models based on this scheme have already been developed and successfully applied (*e.g.* Bathurst and Cooley 1993; Todini 1986). In the following section the mathematical representations of the simulated processes in ESCIMO are briefly described. Generally, the energy balance equation for a snow pack can be expressed as

$$Q + H + V + A + B = \Delta E \qquad (1)$$

where Q is the radiation balance, H the sensible heat flux, V the latent heat flux, A the energy supplied by precipitation, B the soil heat flux and ΔE the change of the energy status of the snow pack for the current time step. The most critical parameter for the simulated energy balance is the snow albedo which depends on many factors (*e.g.* grain size, density or impurity content) and varies for different spectral bands. In ESCIMO, the snow albedo a is modelled using the ageing curve approach (Rohrer 1992)

$$a = a_{\mathrm{min}} + a_{\mathrm{add}}\, e^{-kn} \qquad (2)$$

where k is a recession factor depending on the snow surface temperature and n the number of days since the last considerable snowfall (which causes an increase of the snow albedo to its maximum value). This function is taking into account the evolution of the physical properties of the surface grain which is accompanied with its ageing and has proven its reliability in many applications (*e.g.* Schulla 1997; Plüss and Mazzoni 1994).

The sensible heat flux H is expressed as

$$H = \alpha (T - T_S) \qquad (3)$$

where T is the air temperature, T_S is the snow surface temperature and α is the heat transfer index. α is determined using a function which is derived from measured wind velocity profiles above snow (Escher-Vetter 2001)

$$\alpha = 5.7 W^{0.5} \qquad (4)$$

where W is the measured wind velocity.

The latent heat flux V is calculated after Kuchment and Gelfan (1996)

$$V = 32.82\,(0.18 + 0.098\,W)\,(P - P_S) \qquad (5)$$

where P is the water vapour pressure in the measurement niveau and P_S the one above the snow surface. The surface temperature T_S of the snow pack is estimated using a simplified formula from Ambach (1955) which is based on the heat transfer equation

$$T_S = T_{S*} + 2\,\Delta E \left(\frac{t}{\pi\, k_s\, \rho\, c_{si}} \right)^{0.5} \qquad (6)$$

where T_{S*} is the surface temperature of the snow pack at the previous time step, t is

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the time step in seconds, k_s the thermal conductivity of snow and ρ its surface density. For the disposition of the correct recession factor k for the snow albedo function (Eq.(2)) T_S is set to 273.16 K in the case of positive air temperature or melting condition.

Generally, in mountainous regions the solar radiation is dominant while in lowlands turbulent transfer is the more important component for snowmelt.

The energy supplied by precipitation depends on its phase. If not measured, a threshold temperature is assumed for the distinction between snow and rain (mixed precipitation is not considered). The energy A advected by the precipitation N is calculated for rain with

$$A = N(273.16\, c_{ss} + C_s + c_{sw}(T-273.16)) \tag{7}$$

and, accordingly, for snow

$$A = N 273.16 c_{ss} \tag{8}$$

where c_{ss} is the specific heat of snow, C_S the melting heat of ice and c_{sw} the specific heat of water. The soil heat flux is assumed to be constant and has a value of 2 W/m^2.

The minimum energy E_S needed to start an initial melting process in the snow pack (isothermal state at 273.16 K) is

$$E_S = 273.16\, c_{si}\, Z \tag{9}$$

where z is the snow water equivalent of the snow pack. If the sum of the heat fluxes contributing to the energy status of the snow pack extends E_S, the energy surplus is spent for the melting process. Then the melt water equivalent M is calculated as

$$M = \frac{E-E_S}{C_S} \tag{10}$$

After exhaustion of the energy surplus due to snow melt the new energy content and snow water equivalent of the snow pack are updated for the current time step.

Results

In the following section the results of the modelization with the two snow models CROCUS and ESCIMO for the three subsequent seasons of 1994/95, 1995/96 and 1996/97 and the Col de Porte data are discussed (Fig. 1). The first season (1994/95) is used for an interactive calibration of the snow albedo function parameters ($a_{\min}$, $a_{\max}$ and k) for ESCIMO. The temporal duration of the simulated snow cover is validated by comparing the modelled snow water equivalents with daily snow height measurements; weekly snow water equivalent pit measurements are used for the determination of the mean deviation amount ΔSWE. As a numerical quality measure

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Table 1 – Albedo function parameters and results criteria achieved with CROCUS and different versions of ESCIMO for the three seasons 1994/95, 1995/96 and 1996/97 at the Col de Porte station (1,325 m a.s.l.). The original albedo function parameters found by Rohrer (1992) for the Weissfluhjoch (2,560 m a.s.l.) in the Swiss Alps are underlined.

Season	Albedo function parameters in ESCIMO				Results criteria				
	a_{min}	a_{max}	k (T>0)	k (T<0)	Duration mismatch (days) ESCIMO	Duration mismatch (days) CROCUS	Mean ΔSWE (mm) ESCIMO	Mean ΔSWE (mm) CROCUS	$E_{N\&S}$
94/95	0.5	0.95	0.08	0.03	+ 1	+1	− 3.8	−18.6	0.99
95/96	0.5	0.95	0.08	0.03	+ 1	+2	− 34.4	−32.3	0.99
96/97	0.5	0.95	0.08	0.03	+33	+8	+107.1	−22.5	−0.41
	0.4	0.84	0.12	0.05	+ 9		+ 42.6		0.97
	0.4	0.84	0.20	0.10	+ 2		+ 7.9		0.96

for the correspondence between the CROCUS and ESCIMO simulation results the Nash-Sutcliffe efficiency $E_{N\&S}$ (Nash and Sutcliffe 1970) is calculated. In Table 1 the snow albedo function parameters, the mismatch of the temporal duration of the simulated snow cover and ΔSWE as well as $E_{N\&S}$ are listed for an overview.

In 1994/95, the first snowfalls are observed on December 19th which is the latest since the beginning of the measurements at the Col de Porte. In the beginning of 1995 the observed snow height is 80 cm. The melting period in February is followed by heavy snowfalls and low temperatures in March. After a sunny and warm April the snow cover disappears on May 8th. For the model results it can be seen in Fig. 1 that CROCUS slightly underestimates the measurements in March (ΔSWE = -18.6 mm). Apart from that the two models simulate the evolution of the snow cover accurately and for both the duration mismatch of the disappearance of the snow cover (May 9th) is one day. The snow albedo function parameters for ESCIMO (see Table 1) were interactively chosen to find a minimum for ΔSWE and the duration mismatch. These parameters lead to noticeable higher snow albedo values than the ones found by Rohrer (1992) for the Weissfluhjoch station (2,560 m a.s.l.) in the Swiss Alps (see Table 1). This fact can be either due to predominantly different meteorological conditions and snow types at the two sites for this season or compensating

Fig. 1. Modelization of the SWE for the Col de Porte station (1,325 m a.s.l.) for the calibration season 1994/95 (top) and the two verification seasons 1995/96 (middle) and 1996/97 (bottom) with the snow models CROCUS and ESCIMO. In 1996/97, the results of three ESCIMO versions with different albedo function parameters are compared.

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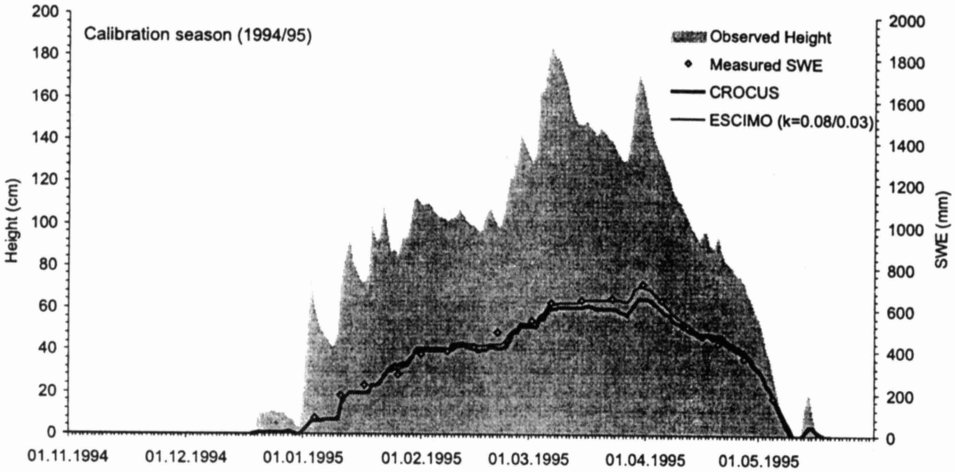

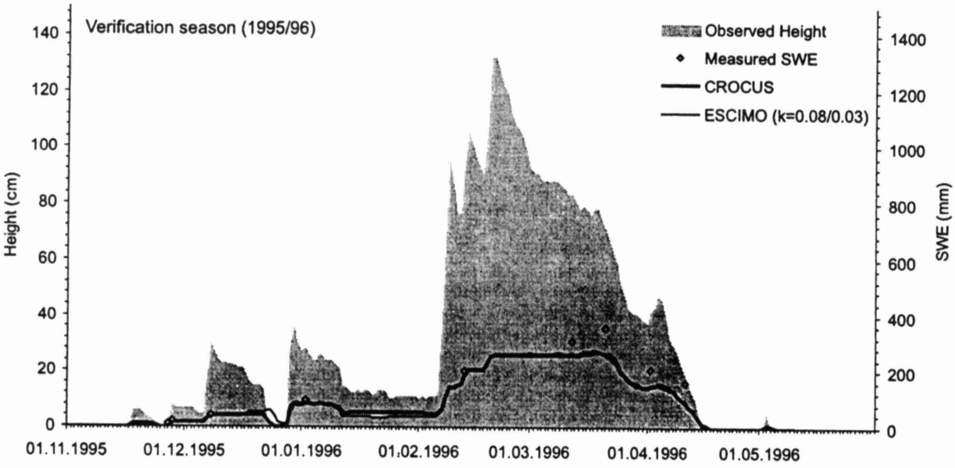

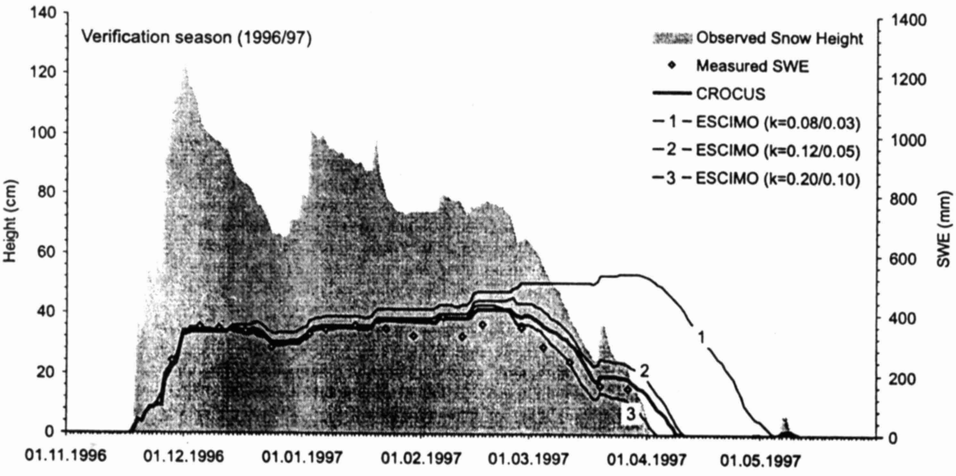

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effects concerning the model algorithms, or (likely) both. The efficiency $E_{N\&S}$ of the two models for the calibration season 1994/95 is $E_{N\&S} = 0.99$.

In the following winter (1995/96), the snow cover disappears twice in the end of November and in the end of December and stays shallow all over January. The snow height reaches the annual mean not until the heavy snowfalls of the second week of February. After this, it melts almost without interruption and disappears on April, 14th. In 1995/96, the simulation with ESCIMO was performed using the snow albedo function parameters adopted for the calibration season 1994/95. Though the short snow-free period in the end of December is not correctly reproduced by ESCIMO, the evolution of the simulated SWE of both models is very similar until the end of the melting season; they miss the day of the snow cover disappearance by one (CROCUS) and two days (ESCIMO), respectively. The apparent overestimation of the measured SWE during the melting season is induced by microtopographic unevennesses or wind transport effects at the pit measurement locations. Therefore, in 1995/96 the ΔSWE is comparably high for both CROCUS (-32.3 mm) and ESCIMO (-34.4 mm), but the efficiency of the two models for 1995/96 again is $E_{N\&S} = 0.99$.

In 1996/97, the strong snowfalls after November the 18th lead to a remarkable snow height of 120 cm. Further considerable snowfalls occur only in the beginning of 1997, but afterwards the snow cover stays on a rather constant niveau until the end of February. Due to the continuous mild conditions during March the snow cover melts quickly and disappears on April the 2nd. Both SWE simulation results are close to the measurements until the beginning of the main melting period in the end of February, but then the ESCIMO results remain on that level until the beginning of April. The main snowmelt period in March is not reproduced leading to a notable overestimation of the SWE and a disappearance of the simulated snow cover occurring 33 days too late. Nevertheless, either CROCUS overestimates the duration of the snow cover by 8 days because of too small melt rates on the last days before its disappearance. From this and the fact that the snow albedo simulation of the two previous seasons lead to accurate results it can be followed that either erroneous precipitation phase measurements occurred or the real snow albedo was unusually low in the end of the season due to the specific properties of the surface snow layer in early spring 1997. Such conditions can be caused by vegetal or other aerosol dust events or a continuously wet and dense snow surface. Because of the significant overestimation of the SWE during the melting period the ΔSWE in 1996/97 is 107.13 mm for ESCIMO (CROCUS: 22.5 mm). As a consequence, the efficiency of ESCIMO and CROCUS for this season is very weak ($E_{N\&S} = -0.41$).

For ESCIMO, the overestimation of the simulated SWE in 1996/97 can be corrected by recalibration of the snow albedo function parameters. Since the snow albedo simulated with the previous version of the function obviously is too high for 1996/97, the smaller a_{min} und a_{max} parameters found by Rohrer (1992) for the Weissfluhjoch (2,560 m a.s.l.) are used as starting point for the optimization (see Table 1). With this original version for the snow albedo function quite reasonable re-

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sults are obtained for 1996/97 (ΔSWE = 42.6 mm, $E_{N\&S} = 0.97$). After further optimization of k (0.2 and 0.1) the ΔSWE is 7.9 mm and the duration of the snow cover is simulated closer to the measurements (2 days) than the result achieved with CROCUS. For theses k values the efficiency of the model results has the significant value $E_{N\&S} = 0.96$.

Conclusions and Outlook

The results of the presented simulations have shown that with a proper formulation of the snow albedo evolution the SWE and duration of a snow cover can also be modelled with sufficient accuracy using the much simpler snow model ESCIMO. For hydrological applications it is a valuable tool, since in physically based, long-time and distributed simulations for large catchments an enormous amount of input data and computing resources are required; thus, there is a strong interest to keep model complexity to the essential minimum.

On the other hand, it should be clearly kept in mind that with the calibration of the snow albedo function all uncertainties of the input data but also all shortcomings of the ESCIMO model structure are equalized. For the data, these uncertainties may include the measurements of precipitation amount and phase, particularly if they have to be interpolated temporally (from daily observations) or for catchment scales. For the model structure, the shortcomings consist of all simplifications concerning the simulation of the energy fluxes, the disregard of internal processes within the snow pack and the simple assumptions that melting conditions only occur at an isothermal state of the snow pack at 273.16 K. Particularly, the formulation of the snow albedo evolution is the main reason for the discrepancies between simulated and observed melt rates due to its significance for the energy available for melt.

The presented comparison shows that with the high complexity in the modelization of the processes the errors in the simulation results are substantially reduced, but the season 1996/97 is an example that even a sophisticated model like CROCUS can notably miss the date of the snow cover disappearance if the parameters are not readapted. Further investigations using the Col de Porte data with the aim to find the causes for the observed discrepancies between the models will include the comparison of the energy fluxes, simulated snow albedos and melt rates for the considered seasons.

Other snow model comparisons have already been performed to assess the suitability of snow models for a wide range of applications. The WMO (1986) organized an intercomparison of models used for operational forecasting of runoff from snowmelt, and the »Project for Intercomparison of Land-surface Parametrization Schemes« (PILPS) has demonstrated the value of intercomparing results from different models and observations for the development of land-surface schemes (Henderson-Sellers *et al.* 1996). Essery *et al.* (1999) compared CROCUS with three oth-

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er snow models at the Col de Porte site. All these previous investigations and the presented one represent pilot studies for the »Snow Model Intercomparison Project« (SnowMIP 2001) which is planned by the International Commission on Snow and Ice to make a detailed comparison of a wide range of snow models using data from several sites with different climate and environmental conditions.

Measurements of the snow albedo, anyway a difficult task, are generally not available, particularly for areas of catchment scale (and snow albedo patterns are spatially and temporally highly variable). For further research in terms of the improvement of snow models with all levels of complexity and their spatial application there is an urgent demand for information about the snow cover albedo with high spatial and temporal resolution. These requirements can be met by remote sensing, because it has the potential to deliver high-resolution, multitemporal snow albedo measurements for all scales. Furthermore, remotely sensed data fields are valuable tools in terms of the initialization as well as the validation of the simulation results. Attempts to derive not only albedo, but also SWE, humidity and other snow model parameters from satellite images have already been performed by *e.g.* Dozier (1989), Krishna (1996), Shi *et al.* (1996), Swami and Brivo (1996), Tait (1996), Wilson *et al.* (1996) and others. In the future, it will be an important goal for further investigations to integrate these data fields into our modelizations.

Acknowledgements

This study was performed during the first authors one year stay as visiting scientist at the Centre d'Etudes de la Neige (CNRM/METEO-France) in St. Martin d'Hères. The authors greatly profited from discussions with Eric Martin (St. Martin d'Hères) as well as Ludwig Braun and Heidi Escher-Vetter from the Bavarian Academy of Sciences (Munich). All these contributions and others not mentioned here are gratefully acknowledged.

References

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P.E., and Rasmussen, J. (1986) An Introduction to the European Hydrological System – Système Hydrologique Européen, 'SHE', 1: History and philosophy of a physically-based, distributed modelling system, *J. Hydrol.,Vol. 87*, pp. 45-59. 2: Structure of a physically-based, distributed modelling system, pp. 61-77.

Arnold, N. S., Willis, I., Sharp, M., Richards, K., and Lawson, W. (1996) A distributed surface energy-balance model for a small valley glacier. I. Development and testing for Haut Glacier d'Arolla, Valais, Switzerland, *J. Glaciol.*, *Vol. 42*, No. 140, pp. 77-89.

Ambach, W. (1955) Über den nächtlichen Wärmeumsatz der gefrorenen Gletscheroberfläche, *Arch. Met. Geoph. Biokl.*, Ser. A, *Vol. 8 (4)*, pp. 411-426.

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Baker, D., Escher-Vetter, H., Moser, H., Oerter, H, and Reinwarth, O. (1982) A glacier discharge model based on results from field studies of energy balance, water storage and flow, *IAHS Publ.*, No. 138, pp. 103-112.

Bathurst, J. C., and Cooley, K. R. (1993) Application of the SHE distributed snowmelt model at three spatial scales (Abstract of a Lecture of the EGS Gen. Ass., Wiesbaden May 1993), *Annal. Geophys., Suppl. I, Vol. 1*, Part II, p. C245.

Blöschl, G., Kirnbauer, R., and Gutknecht, D. (1991) Distributed Snowmelt Simulations in an Alpine Catchment: 1. Model Evaluation on the Basis of Snow Cover Patterns, 2. Parameter Study and Model Predictions, *Water Resour. Res, Vol. 27, No. 12*, pp. 3171-3188.

Braithwaite, R. J., and Olesen, O. B. (1990) A Simple Energy-Balance Model to Calculate Ice Ablation at the Margin of the Greenland Ice Sheet, *J. Glaciol., Vol. 36, No. 123*, pp. 222-228.

Braden, H. (1995) The Model AMBETI, a detailed description of a soil-plant-atmosphere model, *Berichte des Deutschen Wetterdienstes*, Nr. 195, Offenbach am Main.

Braun, L., Brun, E., Durand, Y., and Martin, E. (1994) Simulation of Discharge using Different Methods of Meteorological Data Distribution, Basin Discretization and Snow Modelling, *Nord. Hydrol., Vol. 25*, pp. 129-144.

Brun, E., Martin, E., Simon, V., Gendre, C., and Coleou, C. (1989) An Energy and Mass Model of Snow Cover Suitable for Operational Avalanche Forecasting, *J. Glaciol., Vol. 35, No. 121*, pp. 333-342.

Brun, E., David, P., Sudul, M., and Brunot, G. (1992) A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting, *J. Glaciol., Vol. 38, No. 128*, pp. 13-22.

David, P., and Martin, E. (1997) Le Laboratoire du Col de Porte: Histoire et Climatologie. METEO-France, Centre National de Recherches Meteorologiques, *Note de Travail du Centre d'Etudes de la Neige*, N° 9.

Dozier, J. (1989) Spectral signature of Alpine snow cover from the Landsat Thematic Mapper, *Remote Sens. Environ., Vol. 28*, pp. 9-22.

Escher-Vetter, H. (2000) Modelling meltwater production with a distributed energy balance method and runoff using a linear reservoir approach – results from Vernagtferner, Oetztal Alps, for the ablation seasons 1992 to 1995, *Z. f. Gletscherkd. Glazialgeol., 36 (1)*, pp. 19-50.

Essery, R., Martin, E., Douville, H., Fernandez, A., and Brun, E. (1999) A comparison of four snowmodels using observations from an alpine site, *Clim. Dyn., Vol. 15*, pp. 583-593.

Habets, F., Etchevers, P., Golaz, C., Leblois, E., Ledoux, E., Martin, E., Noilhan, J., and Ottlé, C. (1999) Simulation of the water budget and the river flows of the Rhône basin, *J. Geophys. Res., Vol.104 (D24)*, pp. 31145-31172.

Henderson-Sellers, A., McGuffie, K., and Pitman, A.J. (1996) The Project for Intercomparison of Land-surface Parametrization Schemes (PILPS): 1992-1995, *Clim. Dyn., Vol. 12*, pp. 849-859.

Jordan, R. (1991) A one-dimensional temperature model for a snow cover, US Army Cold Regions Research and Engineering Laboratory Special Report, 91-16, Hanover, NH.

Krishna, A. P. (1996) Satellite remote sensing application for snow cover characterization in the morphogenetic regions of upper Tista river basin, Sikkim Himalaya, *Intern. J. Remote Sens., Vol. 17, No. 4*, pp. 651-656.

Kuchment, L. S. and Gelfan, A. N. (1996) The determination of the snowmelt rate and the

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meltwater outflow from a snowpack for modelling river runoff generation, *J. Hydrol., Vol. 179*, pp. 23-36.

Lehning, M., Bartelt, P., and Brown, R. L. (1998) The mass and energy balance of the SNOWPACK model, EOS, Transactions, American Geophysical Union, Fall Meeting, Supplement, Vol. 79, No. 45, p. F272.

Nash, J. E., and Sutcliffe, J. V. (1970) River flow forecasting through conceptual models (1), a discussion of principles, *J. Hydrol., Vol. 10 (3)*, pp. 282-290.

Rohrer, M. B. (1992) Die Schneedecke im Schweizer Alpenraum und ihre Modellierung, *Zuer. Geogr. Schriften, H. 49.*

Schulla, J. (1997) Hydrologische Modellierung von Flußgebieten zur Abschätzung der Folgen von Klimaänderungen, *Zür. Geogr. Schriften, H. 69.*

Shi, J., Painter, T. H. and Dozier, J. (1996) Estimation of snow surface albedo using Landsat Thematic Mapper, Proc. IGARSS 96, pp. 2249-2251.

SnowMIP (2001) Snow models intercomparison project (http://www.cnrm.meteo.fr/snowmip/).

Strasser, U. (1998) Regionalisierung des Wasserhaushalts mit einem SVAT-Modell am Beispiel des Weser-Einzugsgebiets, *Mü. Geogr. Abhandl., B. 28*, 146 pp., München.

Swamy, A. N., and Brivo, P. A. (1996) Hydrological modelling of snowmelt in the Italian Alps using visible and infrared remote sensing, *Intern. J. Remote Sens., No. 16*, pp. 3169-3188.

Tait, A. (1996) Estimation of snow water equivalent using passive microwave radiation data, Proc. IGARSS 96, pp. 2005-2007.

Todini, E. (1986) The ARNO rainfall-runoff model, *J. Hydrol., Vol.175*, pp. 339-382.

Wilson, L. L., Tsang, L., and Hwang J.-N. (1996) Mapping snow properties for spatially distributed snow hydrological modeling in mountainous areas using passive microwave remote sensing data, Proc. IGARSS 96, pp. 130-132.

WMO (1986) Intercomparison of models of snowmelt runoff, Operational Hydrology Report, 23, World Meteorological Organization, Geneva.

Received: 29 September, 2000
Revised: 20 March, 2001
Accepted: 30 March, 2001

Address:
Ulrich Strasser,
Institute of Hydromechanics and
Water Resources Management,
ETH-Hönggerberg,
CH-8093 Zürich,
Switzerland.

P. Etchevers, Y. Lejeune,
Centre d'Etudes de la Neige,
CNRM, METEO France,
F-38406 Saint Martin d'Hères,
France.

Email: Strasser@ihw.baug.ethz.ch

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